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N66-15240 (ACCESSION NUMBER) (THRU)
23 (PAGES) 1 (CODE)
TMX 56135 (NASA CR OR TMX OR AD NUMBER) 04 (CATEGORY)
FACILITY FORM 602

THE IONIZING RADIATIONS IN SUPERSONIC TRANSPORT FLIGHTS

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Presented at the Second Symposium on Protection Against Radiation in Space

Gatlinburg, Tennessee
October 12-14, 1964

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SUMMARY

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Commercial supersonic transport planes are envisioned to cruise at altitudes up to 23 km or 75,000 feet. The exposure to crew and passengers from Galactic and Solar Cosmic Rays at these altitudes on polar routes is estimated and compared with the maximum permissible dose rates (MPD) cited in the guide lines of the Federal Radiation Council or the International Commission for Radiation Protection.

The dose equivalent in rem from Galactic Cosmic Radiation at cruise altitudes on polar routes is estimated as ≦2 mrem/hr. This implies that the crew should experience ≦20 percent of the MPD for radiation workers (5 rem/year), at 20 hours/week flight duty or 10 hours in 23 km altitude, if evasive measures during intense and energetic solar flare events are taken. The above dose rate from Galactic Cosmic Rays is considered as an upper limit because the fast neutron flux and the buildup factors of secondaries in the airplane are assumed conservatively high.

Estimates of dose rates for the most important intense and energetic flare events (Solar Cosmic Radiation) show that in cruise altitudes at high latitudes and in impact zones, e.g., during the February 23, 1956 event, 1 to 4 rem/hr might have been reached. Such doses are undesirable for the crew and especially for passengers, even if their occurrence is very rare.

If evasive measures are carried out in these cases, such as descending to 40,000 feet (12 km), the radiation doses received by passengers from Solar and Galactic Cosmic Rays appear negligible (≈10 percent of the MPD of 0.5 rem/year at 2 polar flights/month) except for the effects of certain characteristic biological effective components of Galactic Cosmic Rays which appear only in high altitudes, i.e., heavy primaries and stars. These components and also the fast neutron fluxes as they occur in the human body in the passenger plane are not well-known in their intensity except that this intensity is very low (e.g., heavy primaries, ≈1 hit/g/day; stars, ≈1000 hits/g/day) and will not produce a significant ionization dose. More research appears necessary on their fluxes and on their effects at the very low doses, which would be encountered at a reasonable amount of flying, to determine more closely the risk involved for especially sensitive persons such as pregnant passengers and children.

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INTRODUCTION

Supersonic commercial airplanes as they are envisioned for the near future are planned to cruise in altitudes up to about 75,000 feet or 23 km. At this altitude there is only 36 g/cm^2, or 3.6 percent of the mass of the atmosphere above the airplane, which protects against space radiations if their energy is not too high.

This air layer suffices, for instance, to shield against the soft belt radiations and aurora radiations that reach the uppermost atmosphere during magnetic storms; however, it does not suffice to protect against galactic cosmic rays (G.C.R.) which penetrate deep into the atmosphere, down to sea level and below sea level, or against energetic solar cosmic rays, which are observed in some cases also at sea level. In estimating the effects of space radiations on crew and passengers of SST airplanes one is therefore mainly concerned with G.C.R. and energetic solar cosmic rays (S.C.R.).

It might be well to recall in the beginning the maximum permissible exposure levels for normal peace time operations, as listed in the protection guidelines of the International Commission for Radiation Protection (ICRP) or of the Federal Radiation Council.

Table I

Type of exposure	Condition	Dose, rem
Radiation worker:		
(a) Whole body, head and trunk, active blood forming organs, gonads, or lens of eye	Accumulated dose	5 times number of years beyond age 18
	$\left(\frac{5\text{ rem}}{\text{year}} = \frac{100\text{ mrem}}{\text{week}}\right.$	$\left.= \frac{15\text{ mrem}}{\text{day}} = \frac{0.625\text{ mrem}}{\text{hour}}\right)$
(b) Bone	Body burden	0.1 microgram of radium 226 or its biological equivalent
Population:		
(a) Individual	Year	0.5 (whole body)
(b) Average	30 years	5 (gonads)

These low permissible doses for continuing peace time operations - low in comparison to the standards for space crews in the present pioneer period - are the reason that the low level G.C.R. have to be taken into consideration at commercial supersonic transport flights, especially since the G.C.R. produce in SST altitudes a dose rate higher by orders of magnitude and have different characteristics, than the radiations at sea level.

It might be emphasized, that the dose values presented in the following are estimates with emphasis on upper limits. Since not all components and their biological effects are accurately known, a safety factor is included.

GALACTIC COSMIC RAYS

We might recall first some quantitative data on G.C.R. Figure 1 shows the decrease of dose rate toward the equator, or the shielding effect of the earth's magnetic field according to balloon measurements of Neher and Winckler and coworkers. (Reference 1.) It decreases by a factor of 20 during solar maximum years (at an altitude of about 30 km). A second fact is indicated by this figure, namely that the ionization is higher by a factor 2 during solar minimum years than during solar maximum years in latitudes above $\approx 55^{0}$.

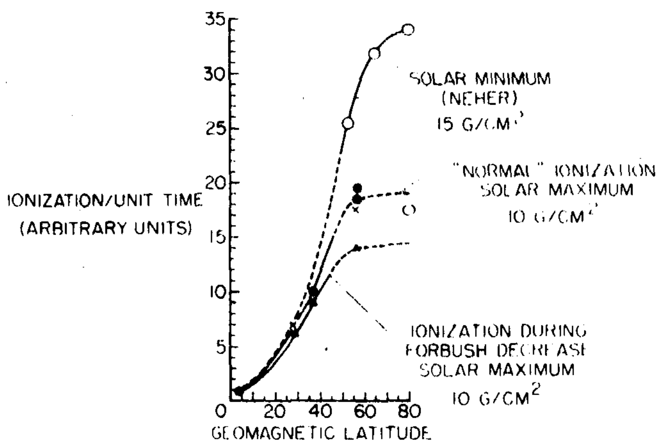


Figure 1.- Total ionization at atmospheric depth of 10 g/cm^2 as a function of geomagnetic latitude at solar minimum and maximum. (From ref. 1, J. R. Winckler.)

We derive from the figure, that the dose rate is highest near the poles and about constant above 50^{0} magnetic latitude during solar activity years. We are, therefore, mainly concerned with the radiation on polar routes.

Figure 2 shows the variation of the particle flux with altitude, especially the transition peak at about 60 g/cm^2 atmospheric depth according to the famous first rocket measurements of Van Allen and Tatel up to altitudes of 160 km.

Figure 3 shows the change of the composition of the G.C.R. beam penetrating through the atmosphere. Down to 36 g/cm^2 from above the nuclear component is prevalent (protons, helions, heavy nuclei, and neutrons, which latter are not included on the figure). At sea level mainly the hard and lightly ionizing component, namely, μ-mesons, are left. We derive from this figure that at SST altitudes we have mainly protons, α and neutrons, which produce in tissue particles with a high linear energy transfer (LET), or ion density along their track if their energy is in the 0.5 to 10 Mev range. The radiation at high altitudes will therefore have a higher biological effectiveness than the lightly ionizing radiations in low altitudes.

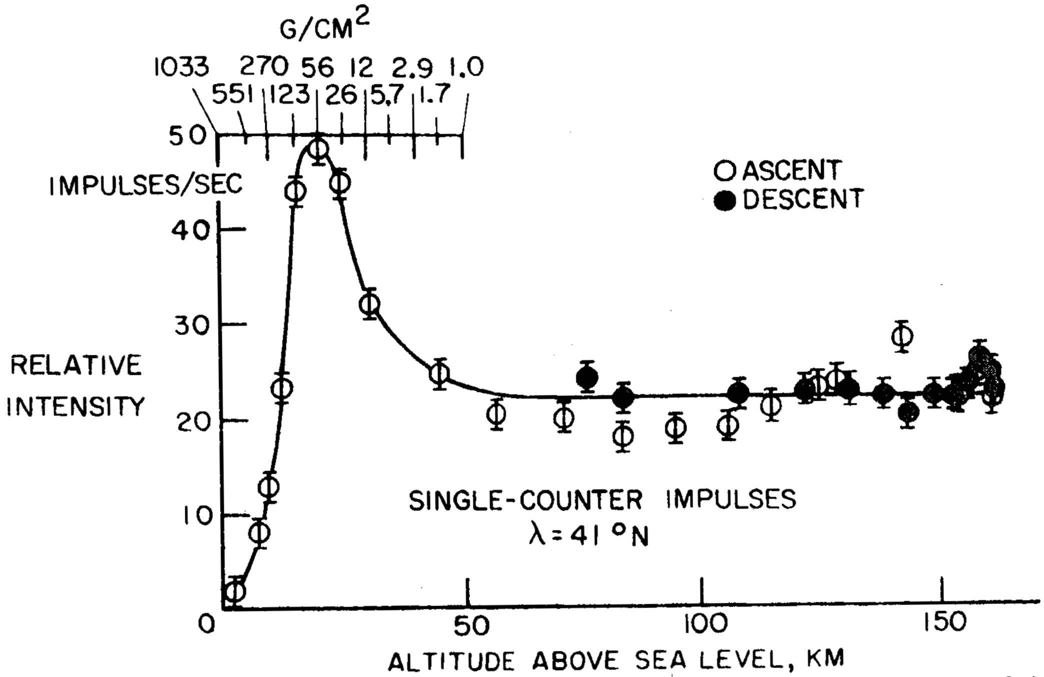


Figure 2.- Total intensity up to very high altitudes measured by unshielded single counter in medium latitudes. (From ref. 2, J. A. van Allen and H. E. Tatel.)

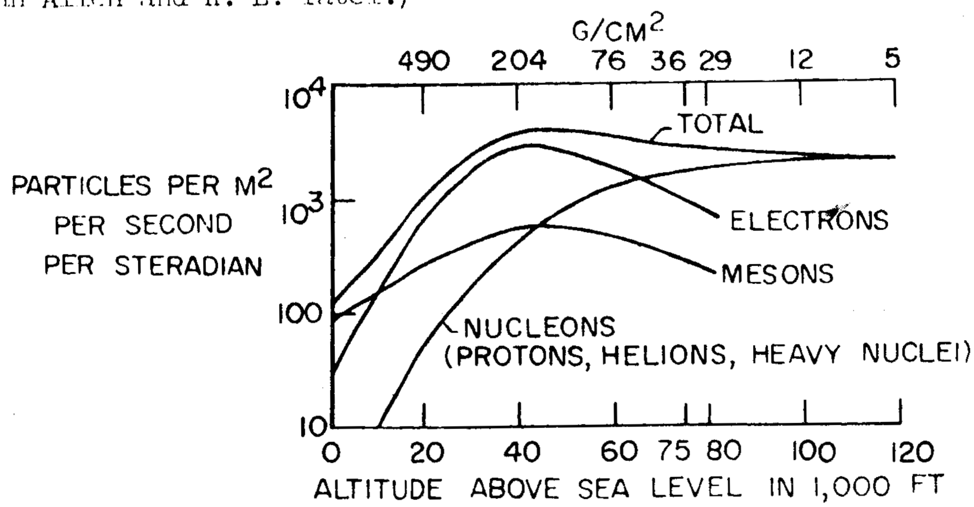


Figure 3.- Altitude profile of particle transition of cosmic ray beam in the atmosphere. (From ref. 3, H. J. Schaefer.)

Figure 4 shows the increase of total ionization with altitude in high latitudes during maximum and minimum years according to balloon measurements of Neher over a period of 20 years. We derive from these measurements two important numbers as basis of our estimates of the exposure at SST altitudes, namely, the overall ionization at 36 g/cm^2 atmosphere depth

(1) During solar activity years of

$$\approx 15\ \frac{\text{mrad}}{\text{day}} \quad \text{or} \quad \approx 100\ \frac{\text{mrad}}{\text{week}} = 0.625\ \frac{\text{mrad}}{\text{hr}}$$

and

(2) During solar minimum years of

$$\approx 20\ \frac{\text{mrad}}{\text{day}} \quad \text{or} \quad 140\ \frac{\text{mrad}}{\text{week}} \approx 0.84\ \frac{\text{mrad}}{\text{hr}}$$

The number for activity years is easy to remember - 100 mrad/week is the same number as the MPD (maximum permissible dose rate) for radiation workers in rem, namely, $100\ \frac{\text{mrem}}{\text{week}} = 0.625\ \frac{\text{mrem}}{\text{hr}}$, or $5\ \frac{\text{rem}}{\text{year}}$.

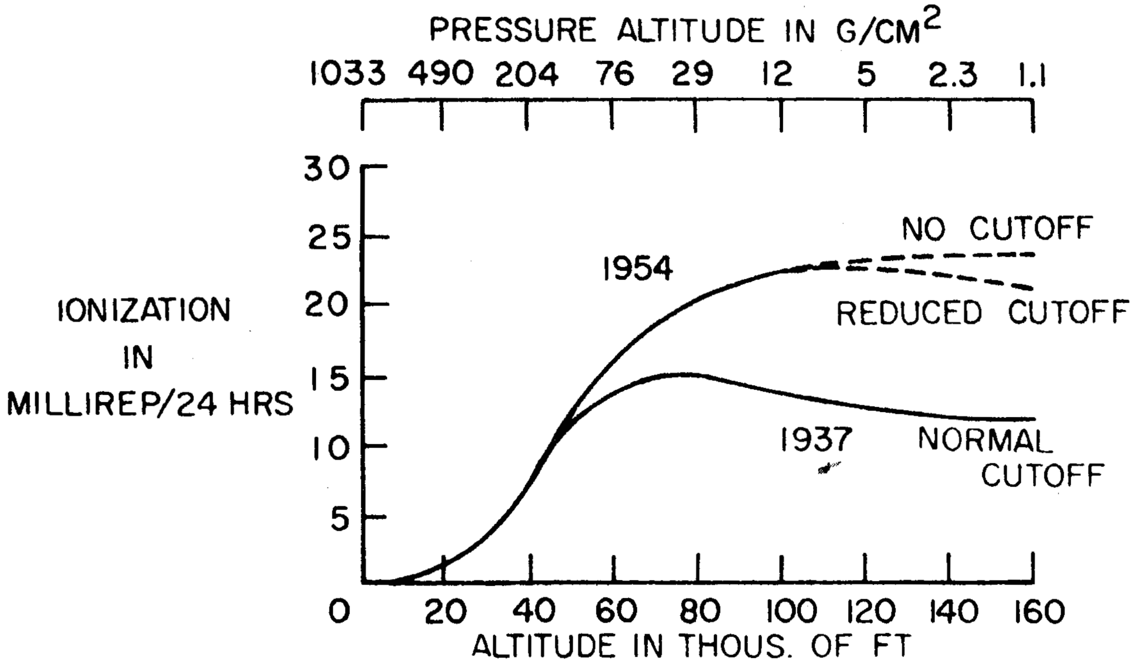


Figure 4.- Altitude profile of the total ionization in a year of high (1937) and low (1954) solar activity. (From ref. 3, H. J. Schaefer.)

The above numbers are rad doses measured in a small ionization chamber. In an SST airplane the surrounding masses of higher Z number and the human body itself produce additional secondaries in nuclear collisions, which increase the rad dose absorbed in tissue. On the basis of measurements of the increase of secondaries under thick layers of material, Van Allen suggested a factor of 2 to 3 for the dose increase at these altitudes below shields of several cm thicknesses of aluminum or steel. If we adopt the factor 2 we would obtain thus as rad dose rates for continuous exposure at 75,000 feet

$$200 \frac{\text{mrad}}{\text{week}} \text{ or } 280 \frac{\text{mrad}}{\text{week}}$$ in solar maximum or solar minimum years, respectively,

or in rad two to three times the MPD.

For the crew of SST, however, the average dose rate remains substantially below the MPD for their professional life, because they are at these altitudes only 1/16.8 of the time (10 hours/week flight time at 75,000-ft altitude). At 80 hours/month flight duty, as is usual today, about 40 hours would be spent in cruising altitudes.

To estimate the rem dose rate or "dose equivalent" (see ref. 4), we have to remember that the radiation in 23-km altitude consists mainly of nuclei especially protons, neutrons, and α-particles. The biologically most effective components are the slow evaporation protons, α's and other nuclei (≈10 Mev energy), which originate in nuclear collisions in the human body, and the energetic neutrons which produce heavy ionizing recoil protons in the hydrogen containing tissue.

Schaefer, Krebs, and especially Van Allen (ref. 5) estimated the biological effects in the human body of the heavy prongs of cosmic ray induced stars by comparison with equivalent amounts of incorporated radium. The star components of low energy being of short range and high specific ionization, resemble closely in energy and ionizing characteristics the α-particles and recoil nuclei from the radioactive decay of radium and its follower products. The number of stars in tissue was estimated by Van Allen, on the basis of measurements in nuclear emulsions at high altitudes, to be 850 per gram of biological material per day. This number of stars is equivalent, with respect to energy deposition, to 0.035μC radium within the human body. This would be 1/3 of the maximum permissible burden of Ra^{226}, at continuous stay at 75,000 feet altitude. If we intend to assess the radiation exposure of the crew, both numbers, that for the ionization rad dose and that for the radium equivalent have to be divided by 16.8 because the crew is in 75,000 feet only about 10 hours/week. (The dose rate in mrad/hr must be multiplied by 10 to obtain the dose per week.) Thus we obtain, as approximate exposure for the crew from Gal. C.R. at high latitudes,

	Fraction of MPD
Overall ionization:	
$2 \times (0.625 - 0.84)\ \frac{\text{mrad}}{\text{hr}} \times 10 = 12.5 - 16.4$ mrem/10 hours (week) . . .	≈15%
Nuclear stars:	
$0.035\mu C\ Ra^{226}/16.8 = 1/3\ MPD/16.8$	≈2%
	≈17%

As was already emphasized by Van Allen this estimate of the "rem" dose or of the biological effect contains large uncertainties. The distribution of stars is uniform throughout the body, while the radium accumulates to 97 percent or more within the bones. Thus the biological effect of the stars may be lower or higher than that of an equivalent body content of Ra^{226}, dependent on whether the concentration near the bone marrow or a uniform distribution over other sensitive organs is more effective.

Furthermore, the number of stars seems to be higher in tissue if one includes 1- and 2-prong stars, which are difficult to observe in photoemulsions. Also the effect of secondary neutrons in tissue is not included except in the factor 2 which was attached to the rad dose. Their energy deposition (recoil protons) is not measured adequately in the ion chambers of Neher, which were filled with argon. The energy deposited by fast secondary neutrons in the human body by means of heavily ionizing recoil protons is substantially higher than the energy imparted to heavy argon atoms. Although the contribution of these neutron recoils to the rad dose is low, the recoils from a fast neutron have a high LET (linear energy transfer) or quality factor.

A more comprehensive approach to estimate the dose equivalent or the rem dose is, to compile measurements and theoretical calculations on the biologically most effective components especially on the neutrons and on charged heavily ionizing particles, and on their spectra, and to multiply their flux in the different energy ranges with their dose conversion and quality factors for this energy range.

On the basis of neutron data of Hess et al. (ref. 6), Sobermann (ref. 7), Lingenfelter (ref. 8), Lal et al. (ref. 9), Korff, Haymes et al. (ref. 10), and the calculations of Patterson et al. (ref. 11), S. P. Shen (ref. 12) comes in this way to the result that the neutrons in air would produce a rem dose* of at most twice the rad dose measured in an Argon ionization chamber at SST altitudes and high latitudes. The primaries and secondaries in air produce in tissue about 850 to 1,000 stars/g-day as mentioned before. If each star deposits locally about 50 Mev on the average, the resulting physical dose would be 0.03 mrad/hr. If a quality factor of 10 for the heavy ionizing components and recoils is assumed, the dose equivalent in rem would than be 0.3 mrem/hr or ≈40 percent of the ionchamber dose rate in rad/hr. Because of the implied conservative assumptions on fast neutron flux and energy deposit and quality factor of stars, we assume here, that the dose equivalent in rem from neutrons and stars combined is equal to the ionchamber dose in rad. Taking again into

*The neutron flux to dose conversion factors are taken from Handbook 63 "Protection Against Neutron Radiation up to 30 Million Electron Volts." U.S. Department of Commerce National Bureau of Standards, November 1957.

account by a factor of 2 the secondaries produced in the environmental masses of the airplane of higher z-number than air, the dose balance in the airplane in 75,000 feet in high latitudes would than be at most the following:

Rad dose from charged particles (ion chamber)	$100 - 140 \frac{\text{mrad}}{\text{week}} = 0.625 - 0.84 \frac{\text{mrad}}{\text{hr}}$
Maximum neutron and star rem dose (including that produced by secondaries from the airplane)	$200 - 280 \frac{\text{mrem}}{\text{week}} = 1.25 - 1.67 \frac{\text{mrem}}{\text{hr}}$
	$1.9 - 2.5 \frac{\text{mrem}}{\text{hr}}$

or three times the ion chamber dose rate.

The high contribution from neutrons is based on the assumption that the fast neutron flux in these altitudes corresponds to the spectrum calculated by Hess in ≈ 40 g/cm^2 atmospheric depth from data in (ref. 6) and that the flux of secondaries is doubled by the aircraft. Unfortunately while the approximate shapes of the neutron spectra are fairly well known, the absolute flux values are still uncertain. More recently direct measurements with detectors that are highly selective to fast neutrons (1 to 10 Mev), by Mendell and Korff (ref. 13) gave neutron intensities in these altitudes that were lower by a factor of about 3.

On the basis of the more conservative assumptions the exposure of the crew at 10 hours/week duty in 75,000 feet on high latitude routes would then be about 19 to 25 percent of the MPD; corresponding additions have to be made for ascent and descent. The exact values depend on the contribution of neutrons which is uncertain by a factor of 3 and the contribution of secondaries from the airplane which is difficult to calculate and may have to be measured for different types of aircraft.

At altitudes of 10 to 11 km (30 to 35,000 ft) where our subsonic jets of today cruise, the ion chamber dose rate in high latitudes and the neutron flux is lower by about a factor of 3. The number of stars is, however, at least smaller by a factor of 4.

The ion chamber dose is (see fig. 4):

$$\approx 5 \text{ mrad/day} = 0.21 \text{ mrad/hr}$$

Because the radiation in these lower altitudes contains fewer nucleons and nuclei the production rate of secondaries in the structure of the airplane and of stars and recoils in the human body is smaller than in high altitudes. We allow therefore only a factor of 2 to the ionchamber dose rate as the quality and buildup factor and obtain about 0.4 mrem/hr as a rough approximation for the less biological effective radiation at 30 to 35,000 feet or 9 to 10.5 km altitude in high latitudes.

HEAVY PRIMARIES

With respect to heavy primaries I might add here only a short remark on their frequency at 75,000 feet in high latitudes.

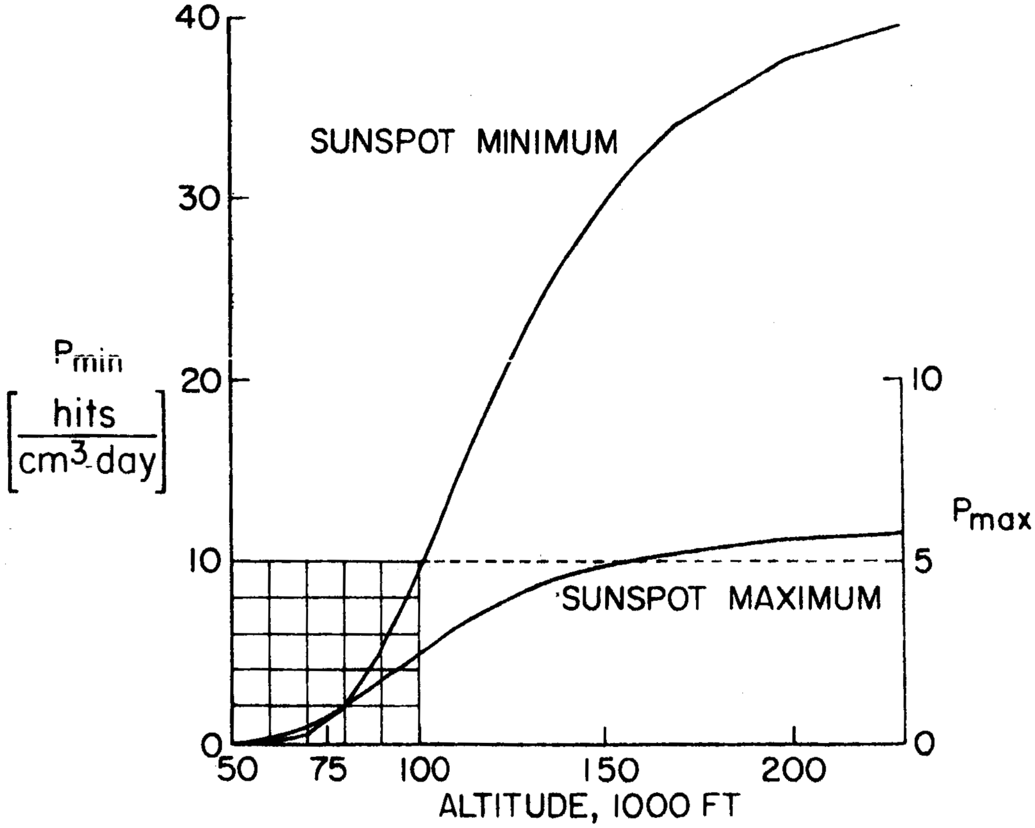


Figure 5.- Variation of thin-down intensity with altitude for seasons of maximum and minimum sunspot activity. (From ref. 14, H. Yagoda.)

The compilation of balloon flight measurements of Yagoda in figure 5 shows that in 75,000 feet about 1 hit/cm^3/day is obtained. Furthermore from the comprehensive theoretical studies of H. Schaefer (ref. 3) it can be seen that the heavier primaries ($Z > 20$) can penetrate only very seldom to these relatively low altitudes.

Thus the above number of hits is mainly produced by the lighter nuclei C,N,O - up to N_e (More data on heavy primaries and on considerations of their effects are given in references 15 and 22 and references therein).

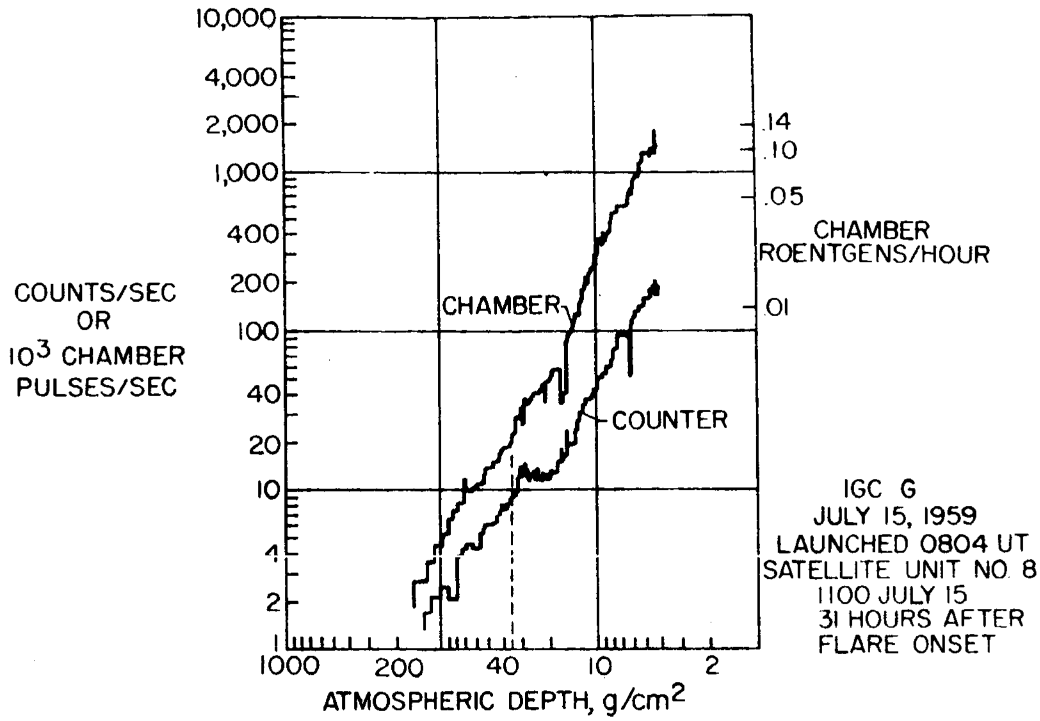
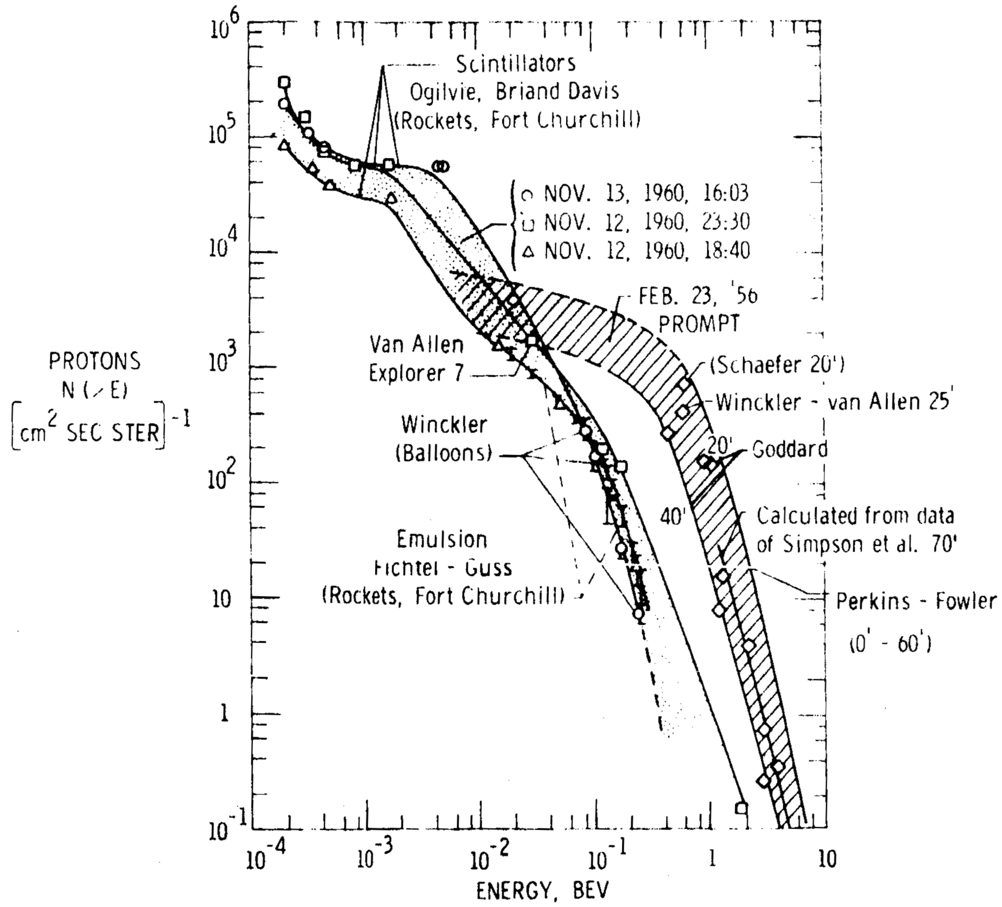


Figure 6.- Altitude dependence during a period of high intensity. This flight ascended between 0800 and 1100 universal time on July 15, 1959. (From ref. 1, J. R. Winckler.)

In figure 6 dose rates actually measured within the atmosphere at a low energy event of extreme size (July 14, 1959) are given. By low energy event is understood an event in which the particle spectra fall off steeply with energy and no relativistic particles are measured ($E \lesssim 300$ Mev). Such extreme events occurred with a frequency of 1 to 3 per year during the 3 years of maximum activity of the last solar cycle. At a depth of 5 g/cm^2 about 0.14 rad/hr was measured, and at a depth of 36 g/cm^2 about 1 mrad/hr is estimated. These dose rates were valid 29 hours after onset of the solar event in the decreasing phase of the event and may have been higher by a factor of 10 at the peak of the event, i.e., 10 mrad/hr. Because of this low dose rate it seems justifiable, therefore, to consider the low energy events as a minor hazard, even though the dose contribution from neutrons was not measured in the nitrogen chamber and is not included. Three such events occurred in 1959. (May 12, July 10, and July 14.)

A fourth extreme event, on July 16, 1959, called "medium energy event" was of greater significance. An increase of neutrons at sea level was observed which implied particles with energies above 500 Mev, which penetrate much deeper into the atmosphere and produce energetic secondaries which reach sea level. Its spectra were similar in intensity and energy to those of the November 12 (and November 15) event in 1960, which are more completely known.



The numbers 20', 25', ... are the minutes after solar cosmic ray onset, observed on earth 0350.

Figure 7.- Flare-particle spectra.

We consider here the spectra on November 12, at 23^{30} U.T., and on November 13, 16^{03} U.T. (fig. 7) 10 and 27 hours, respectively, after the particle flux onset. The two spectra are determined from measurements with rockets in Fort Churchill launched by Goddard scientists, from the measurements of Winckler with balloons and from the measurements of Van Allen and Lin with Explorer VII. Furthermore, the neutron measurements at Deep River by Carmichael, Steljes, and McCracken are taken into consideration (ref. 15, and references therein cited).

By far the highest doses at SST altitudes are produced by "high energy" events such as that of February 23, 1956. In this case the sea level monitors recorded a neutron increase of 3600 to 5000 percent in high latitudes or in impact zones, respectively. During the November 1960 "medium energy" events the neutron monitor in Deep River (Canada) recorded a maximum increase to 225 percent only. In the same figure 7 approximate prompt spectra of the February 23, 1956 high energy event are shown. The intensities in the 700 Mev range were of the same order of magnitude as those of medium energy events in the 70 Mev range (about 500 to 1,000 particles/cm^2 sec sterad). Because of the large flux of high energy particles this would have been the most important event of the last cycle with respect to implications to the SST. Unfortunately its fluxes between 100 and 1,000 Mev are not as well known as the intensities of the November 12 event; however, based on the spectra of Simpson, measured 1 to 10 hours after onset (ref. 16), and on the balloon measurements of Van Allen and Winckler (refs. 17 and 18) and the estimates of Fowler and Perkins, Bristol, Great Britain (ref. 19) derived from the 50-fold increase of neutrons in Leeds, England, the spectra for the first hours lie in the broad strip indicated in figure 7. The measurements are extrapolated to lower energies by the dashed lines.

We see the Simpson 0500 U.T. Spectrum 70' after C.R. onset (flare max 0342), the estimate of the Goddard group for 0430, the extrapolation back to the time of the maximum of the Chicago monitor (0415) on the basis of balloon measurements about 19 hours later by Van Allen and Winckler, and estimate from H. Schaefer based on the 3600 percent neutron increase in the Durham monitor. The estimates of the Bristol group are substantially higher in the low energy range and are only used down to ≈900 Mev.

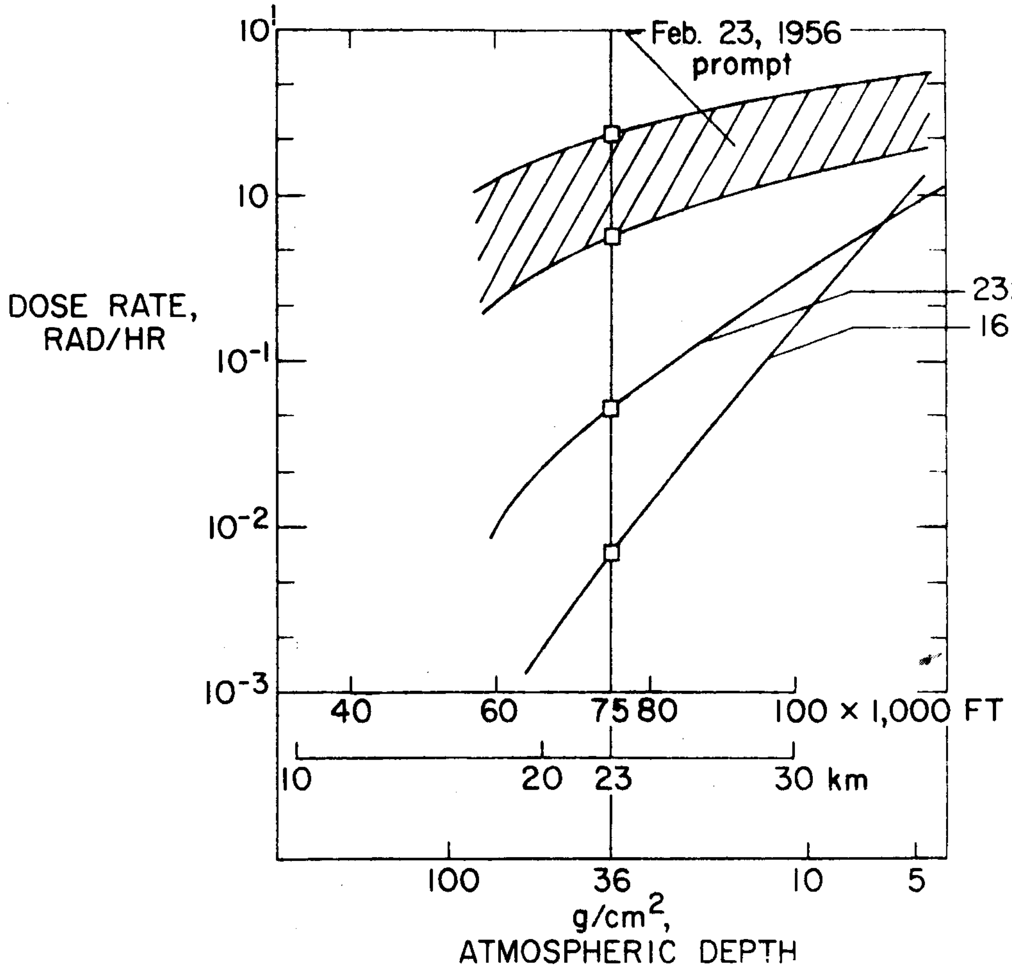


Figure 8.- Dose rates within the atmosphere from solar flare particles (high magnetic latitudes).

The dose rates within the atmosphere derived from these spectra for the 12 November 1960 medium energy event and the February 1956 high energy event are shown in figure 8. At 36 g/cm^2 altitude are obtained: on November 12, 1960: 50 $\frac{\text{mrad}}{\text{hr}}$, on February 23, 1956: 0.5 to 2 $\frac{\text{rad}}{\text{hr}}$ in the early phases.

One sees that about 10 1-hour trips during medium energy events are needed to obtain the same dose as that produced by the February 1956 event in one of its first hours in 75,000-foot altitude.

It may be mentioned that nuclear collisions and their secondaries, especially neutrons, are not taken into account in these calculations. For medium energy events like that of November 12 in a recent paper Lingenfelter and Flamm (ref. 20) estimate the contribution of neutrons to the rem dose in approximate calculations. For an atmospheric depth of 30 g/cm^2 the result is obtained that the rem neutron dose is of the same magnitude as the dose produced by the primary protons. In higher altitudes the primary dose exceeds the n-dose, in lower altitudes the neutron rem dose is the larger. The February 1956 event with its much higher intensities in the high energy range is not treated in reference 20. The rad doses in 36 g/cm^2 of 1/2 to 2 rad/hr would have to be multiplied by a factor of about 2 to account for the secondaries. Thus, as a rough upper estimate, 1 to 4 rem/hr are obtained from the prompt spectra of figure 8. Events comparable to the February 1956 event in intensity and energy occurred only one or two times per cycle during the last three 11-year periods. They occur apparently during the rising or descending phases of the sunspot cycles, as figure 9 indicates.

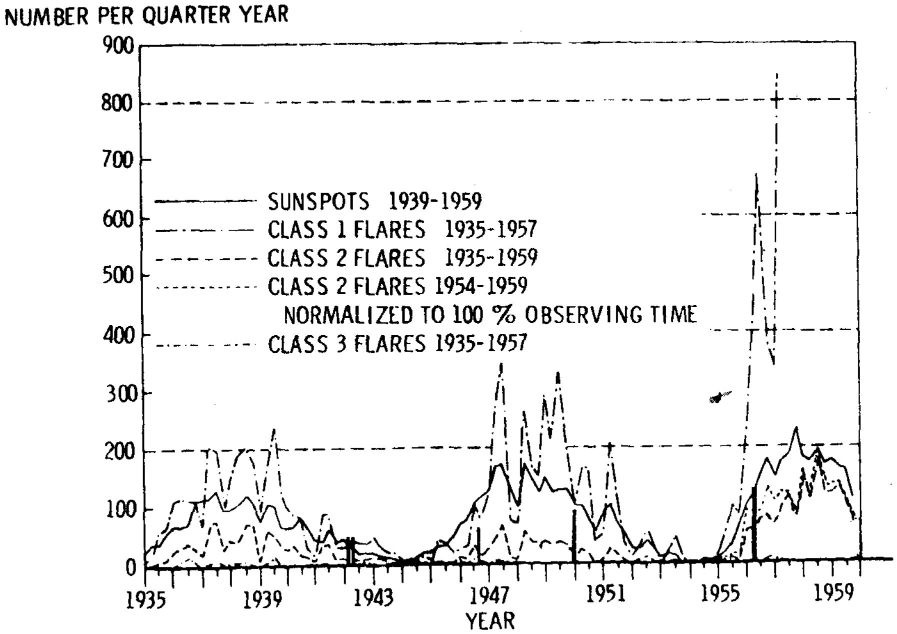


Figure 9.- Frequencies of sunspots and flares in the last solar periods and high-energy proton events. (Courtesy J. W. Evans, Sacramento Peak Observatory, New Mexico.)

More information about these events is contained in figure 10.

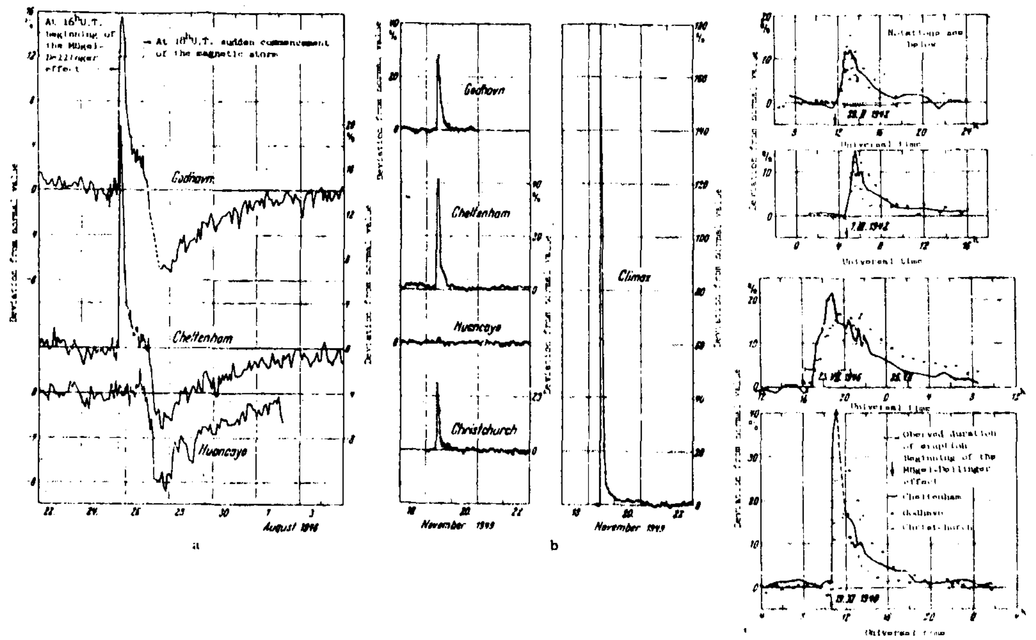


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Figure 10.- Intense high energy solar events 1942 to 1949, observations with ionization chambers on different stations.
a. Increase of cosmic ray intensity on 25.VII.1946.
b. Increase of cosmic ray intensity on 19.XI.1949.
c. Increase of cosmic ray intensities during the sun eruptions of 28.II.1942, 7.III.1942, 25.VII.1946, and 19.XI.1949 at different stations. (Reproduced from ref. 21.)

The figure shows the increase of C.R. intensity at sea level and at mountain level measured in ionization chambers covered by 10 cm lead, indicative of the meson and electron components produced mainly by primaries of very high energy. Unfortunately neutron monitor data are not available for these earlier high-energy events. Thus a comparison with respect to spectra in the low Bev and hundreds Mev range with the February 1956 event can not be made. The meson and electron increase in these ion chambers is a measure of the more energetic particles in the multi Bev range and not, as the neutron increase in pile monitors, of the lower energy particles, which are of most interest in SST altitudes. Nevertheless it is interesting to note that during the November 1949 event the increase within the ion chamber at Cheltenham (50° N. magn. latitude) was 40 percent in comparison to 80 percent in February 1956.* This indicates that the spectra in the high-energy range were of comparable magnitude. It may be mentioned also that the intensity in impact zones may have been higher than at the medium latitudes where Gal. C.R. monitors were located.

*Personal communication of Dr. Scott I. Forbush.

SUMMARY ON EXPOSURE OF CREW AND PASSENGERS ON POLAR ROUTES

In table II the exposure of the crew under extreme conditions, i.e., on polar routes, averaged over the 11-year solar cycle is summarized according to these rough estimates. The crew flight time is assumed to be 80 hours/month of which 40 hours are at 23 km (75,000 ft) altitude. Exposure during ascent and descent is disregarded. The frequency, durations, and spectra of flare events important in SST altitudes are taken as those of the last solar cycle, which was the most active cycle of this century. No evasive measures such as diving to lower altitudes, if a flare event is in progress, are assumed. There is no indication that events of larger size (larger intensity and duration of the penetrating components) than the February 1956 event cannot occur; however, they should be very rare.

From table II it is seen, that the average rem dose rate from Galactic and solar C.R. would amount to about 30 percent of the MPD of 5 rem/year, i.e., ≈1.5 rem/year. For the crew the main contribution, i.e., 21 percent of the MPD comes from Gal. C.R. It is difficult to say how trustworthy this number is, since the contribution from additional secondaries originating in the airplane and especially the contribution of neutrons is not well known. It should be however, at most, too high by a factor of 2. Furthermore, since the crew will probably be on duty for a maximum of 25 years the MPD for radiation workers referring to 50 years duty is not directly applicable and is cited here only to have a rough comparison with the maximum permissible radiation exposure in other professions. Taking evasive measures in case of energetic flare events the exposure of the crew on polar routes would be ≲20 percent of the MPD of 5 rem/year at flight duty time as usual at present.

TABLE II

CREW, WITHOUT PRECAUTIONS

[Upper limits of exposure, polar routes 40 hour/month duty at 75,000-foot (23-km) altitude (not including ascent and descent)]

(1) GALACTIC C.R.	Continuous stay		10 hr/week duty at 75,000 ft		Average for 11-year cycle	Fraction of maximum permissible (5 rem/yr)
	Sol min	Sol max	Sol min	Sol max		
Ionchamber	0.84	0.625 $\frac{\text{mrad}}{\text{hr}}$				
Dose equivalent produced by primaries, secondaries (also from the airplane), and their collisions in tissue (stars, neutron recoils)	2.5 $\frac{\text{mrem}}{\text{hr}}$	1.9 $\frac{\text{mrem}}{\text{hr}}$	1.3 $\frac{\text{rem}}{\text{yr}} \times \frac{2}{11}$	1.0 $\frac{\text{rem}}{\text{yr}} \times \frac{9}{11}$	1.06 $\frac{\text{rem}}{\text{yr}}$	21 percent
Heavy primary hits	1 $\frac{\text{hit}}{\text{cm}^3\ \text{day}}$		0.4 $\frac{\text{hit}}{\text{cm}^3\ \text{week}}$		20 $\frac{\text{hits}}{\text{cm}^3\ \text{year}}$	?
(2) SOLAR EVENTS Medium energy: ≤1/year (4 yrs)	During activity years 2 round trips per event (4 hrs) $1\ \frac{\text{event}}{\text{year}} \times 4\ \text{hours} \times \leq 100\ \frac{\text{mrem}}{\text{hour}} \times 4\ \text{years}$ or $0.4 \times \leq 4\ \text{rem} \leq 1.6\ \text{rem}$					
High energy: $\left(\frac{1\ \text{extreme event or } 2 \text{ to } 3 \text{ major events}}{11\ \text{years}}\right)$	$1\ \text{trip}\ (1\ \text{hr}) \times \leq 4\ \frac{\text{rem}}{\text{hr}} \leq 4\ \text{rem}$ $\leq \frac{5.6\ \text{rem}}{11\ \text{years}}$				0.5 $\frac{\text{rem}}{\text{year}}$	≤10 percent

Maximum permissible dose rate for radiation workers. } = 5 rem/yr Total ≤1.6 rem/yr ≤31 percent

TABLE III

PASSENGERS, WITHOUT PRECAUTIONS

[Upper limits of exposure, polar routes]

(1) GALACTIC C.R.	Continuous in 75,000 feet	Level for two flights per month of 1 hour each		Fraction of MPD
Stars:	850 to 1000 $\frac{\text{stars}}{\text{cm}^3\ \text{tissue/day}}$	$\approx 75\ \frac{\text{stars}}{\text{cm}^3\ \text{month}}$ $\approx 2\ \frac{\text{stars}}{(3\text{mm})^3\ \text{month}}$		?
Heavy primaries:	$1\ \frac{\text{hit}}{\text{cm}^3\ \text{tissue/day}}$	$\frac{1}{12}\ \frac{\text{hit}}{\text{cm}^3\ \text{month}}$ $\approx 2.3 \times 10^{-3}\ \frac{\text{hit}}{(3\text{mm})^3\ \text{month}}$		
(2) SOLAR EVENTS	Encountering all energetic events of solar cycle		During 11 years	
Medium energy:	1 trip per event (1 hr)			
1/yr (4 yrs)	$\frac{1}{\text{yr}} \times 1\ \text{hr} \times \leq 100\ \frac{\text{mrem}}{\text{hr}} = 100\ \frac{\text{mrem}}{\text{yr}} \times 4$ yrs		≤ 0.4 rem	
High energy:				
$\left(\frac{\text{1 extreme event or 2 to 3 major events}}{\text{11 years}}\right)$	1 trip (1 hr) $\times \leq 4\ \frac{\text{rem}}{\text{hr}}$ per 11 yrs		≤ 4 rem	
	Total		$\frac{\leq 4.4\ \text{rem}}{11\ \text{yrs}}$	
			≤ 0.40 rem/yr	≤ 80 percent

One-time maximum dose 1 to 4 rem in 1 hr

MPD maximum permissible dose rate for population. } = 0.5 rem/yr

The exposure of passengers under extreme conditions and without evasive measures in case of solar events, is given in table III. We assume here 2 flights = 2 hours/month, that is 24 hours flight time per year in 23 km altitude on polar routes. For such short periods the overall ionization dose in rem from Galactic C.R. is small and may be neglected. With respect to the question, first discussed by Hermann Schaefer, concerning pregnant female passengers we mention the number of heavy primary-hits/cm^3. The foetus is most sensitive to irradiation in the early differentiation stage between 14 days and 6 weeks and has in this period a volume of $\approx$0.5 to 1.2 cm^3. If we assume a sensitive volume of (3 mm)^3 the 2.3×10^{-3} hits/(3 mm)^3/month, would afflict 2.3 of 1,000 female passengers pregnant in the second month, who fly 2 times in this period. Furthermore, from the number of stars of 850 to 1000/cm^3 tissue/24 hours would be obtained on the average 2 stars/(3mm)^3/month for the same passengers. Because of the uncertainties with respect to the size of the sensitive volume, which is assumed rather arbitrarily, the uncertainties in the number of heavy primary hits and the effectiveness of heavy primaries and stars, there is no proof as yet that their effects on these passengers can be completely neglected.

Without evasive measures the dose for passengers from solar events are estimated as high as 4.5 rem per 11 years, if we make the extreme assumption that this passenger encounters all major energetic events of the solar cycle. This would be an average dose rate of 0.4 rem/year or 80 percent of the maximum permissible dose rate of 0.5 rem/year for a small part of a population pool. Because of the low probability of encountering such events this fact is however considered as of no genetic significance. More pertinent is the fact that the main part of the flare event doses would occur in a very short time, that is in about 1 hour. A dose of 1 to 4 rem in 1 hour appears not desirable especially for pregnant female passengers and children. Such exposure can be avoided by evasive measures, e.g., of diving down to lower altitudes of about 40,000 feet in case of such major events and by continuation of the flight to its destination under a protective air cover of about 200 g/cm^2. The dose values given here are lower by a factor of approximately 2 than the numbers given by this author in references 22. Higher multiplication factors for the influence of the airplane and very conservatively extrapolated flare particle spectra based on early data were used in those articles. Even the lower factor 3 given here to obtain the dose equivalent in rem of G.C.R. from the ionchamber dose is still considered as conservative, since the fast neutron flux is apparently lower than previously assumed and a factor 2 for buildup of secondaries by structural elements of the airplane as the fuselage having a Titan wall thickness of ≈ 1 g/cm^2 appears highly conservative.

In summary it might be said:

If appropriate precautions are taken - as diving down to sufficiently low altitudes or rerouting of the airplane to lower geomagnetic latitudes in case of energetic solar events - the ionization exposure of passengers and crew in supersonic flights lies significantly below the maximum permissible dose rates, as defined by the Federal Radiations Council or ICRP for the commonly known more lightly ionizing radiations (protons and neutrons and even including α). No permissible dose for heavy primaries is stated (for protection purposes), or for recoils and certain components of stars which are uniformly distributed through the human body. These components are a new and in low altitudes unknown or at least inadequately explored phenomenon.

Indications are that such heavy ionizing components are very effective in germinating tissue. On the other hand, their intensity in SST altitudes up to 23 km is very low and not well known. It might be therefore advisable for sensitive passengers to avoid exposure to this kind of radiation until there is proof that the effects of such low intensities can be neglected.

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NASA-Langley, 1965